



Center for Autonomous Vehicle Research

Mechanical & Aerospace Engineering

Wireless Communication Networks Between Distributed Autonomous Systems Using Self-Tuning Extremum Control

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Milestones

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❖ Motivation and Issues

❖ Comms Propagation Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results



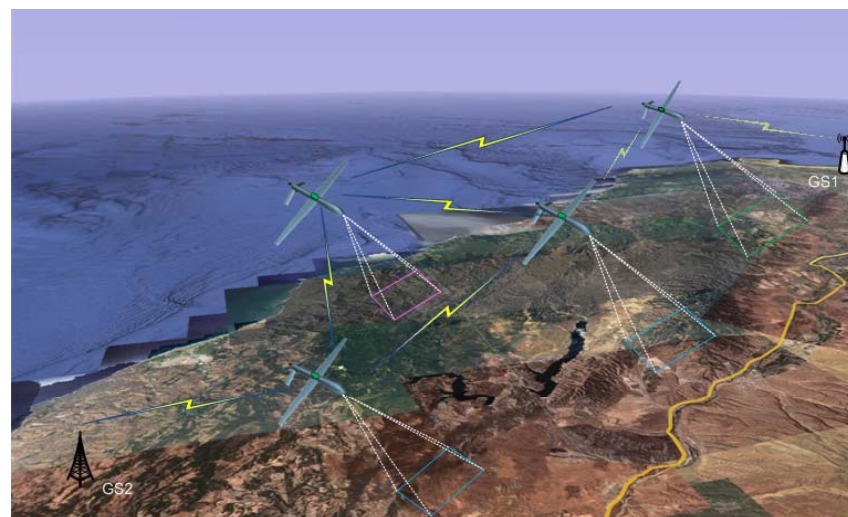
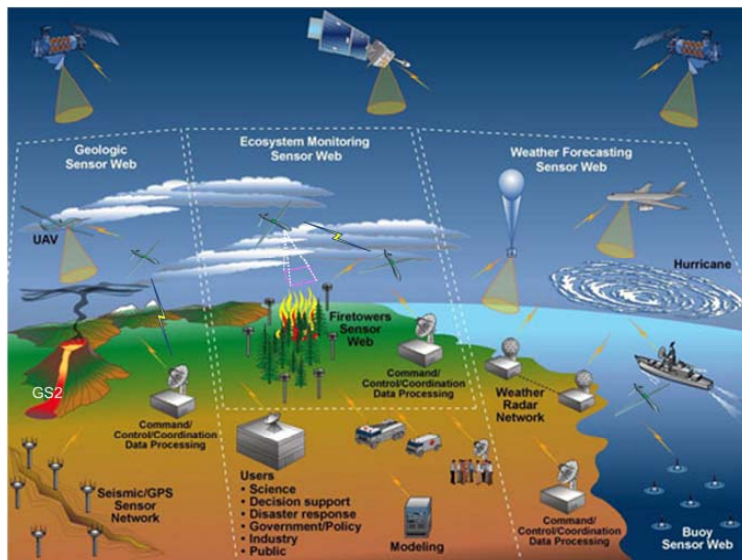
Sensor Networks with Multiple UAS

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❖ Applications

- Nature Monitoring - Civil (Disaster, Forest Fire, Weather)
- Surveillance & Coverage - Military (SA, Decision Support, ISR)
- Remote Sensing - Science (GIS, Ocean Map Building, etc)





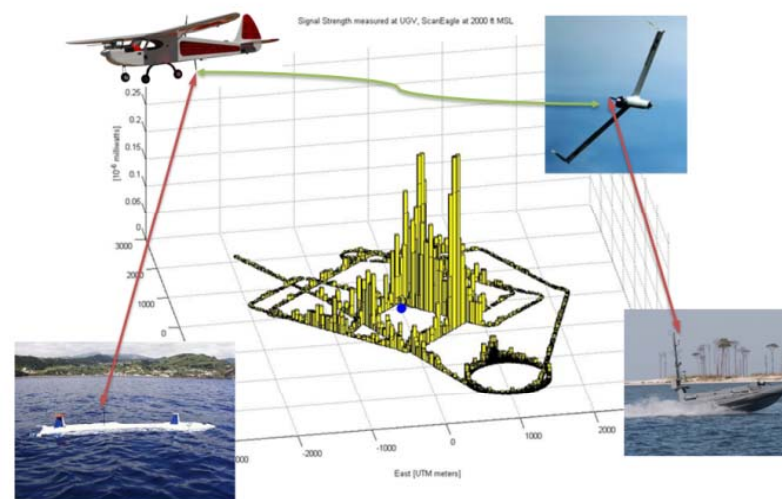
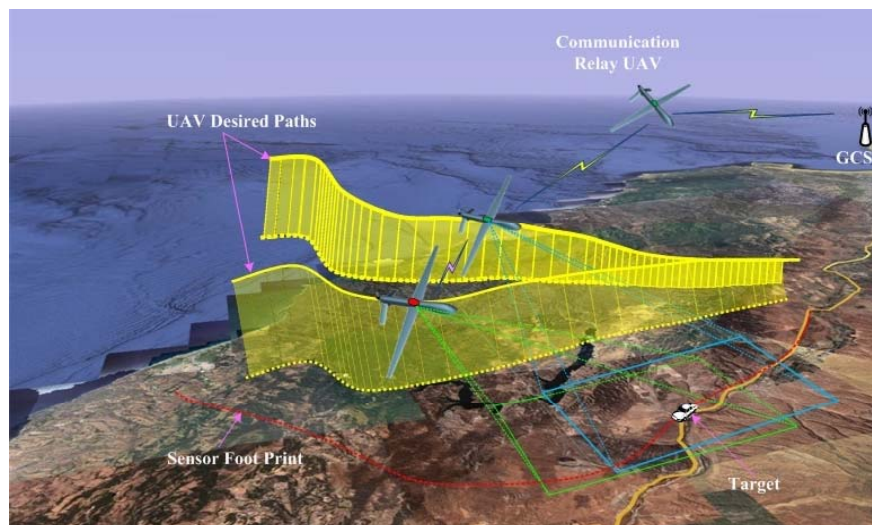
Research Goals & Issues

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❖ Research Goals

- ❑ Dispatch a swarm of networked UAVs as communication relay nodes for real-time decision-making support and situational awareness





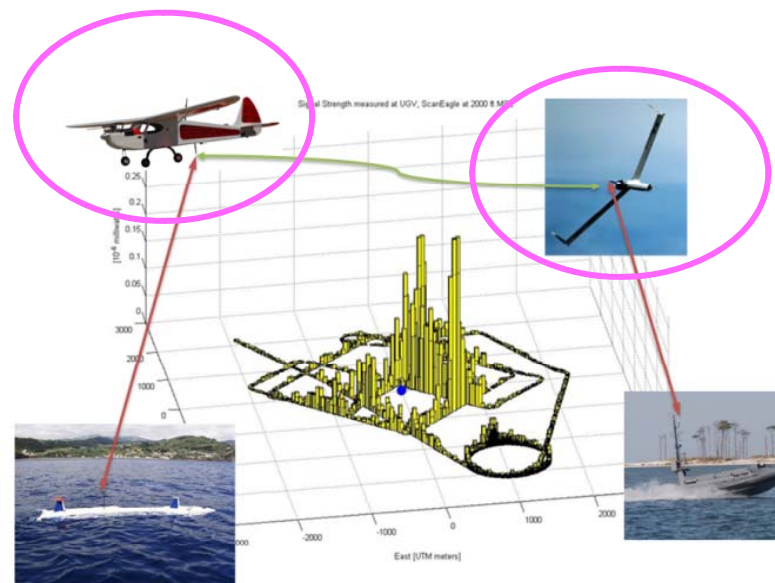
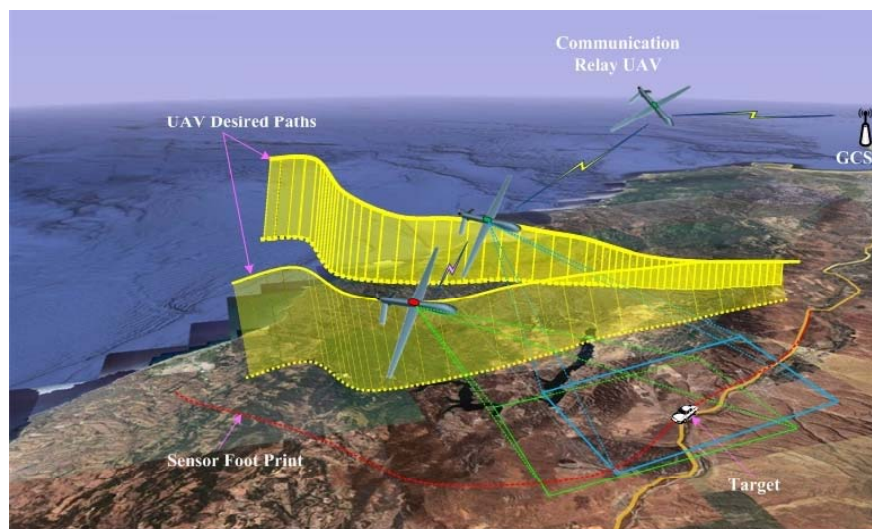
Research Goals & Issues

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❖ Research Issues

- ❑ High Bandwidth Communication Links (Max. Throughputs)
- ❑ Wide Area/Range Coverage (Network Coverage Control)
- ❑ Long-Term Communication Relay (Aerial Platforms)





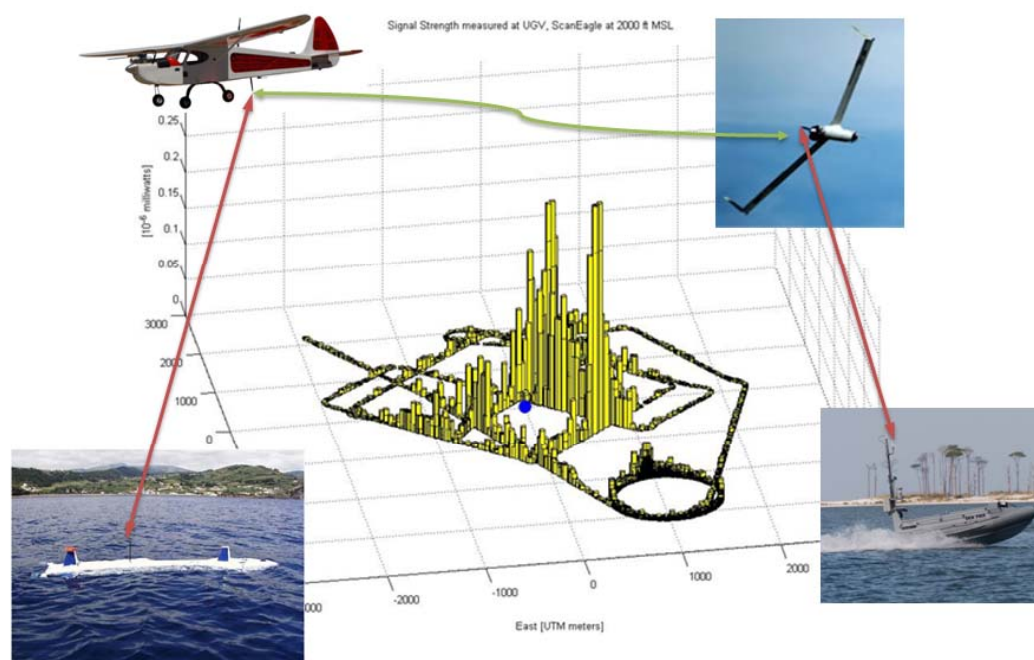
Maximum Comms Networking

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❖ Objective and Approach

- ❑ Develop control algorithms that allow UAVs to **reposition themselves autonomously at optimal flight location** to maximize the communications link quality



Concept for Sensor Networking Between Heterogeneous Vehicles



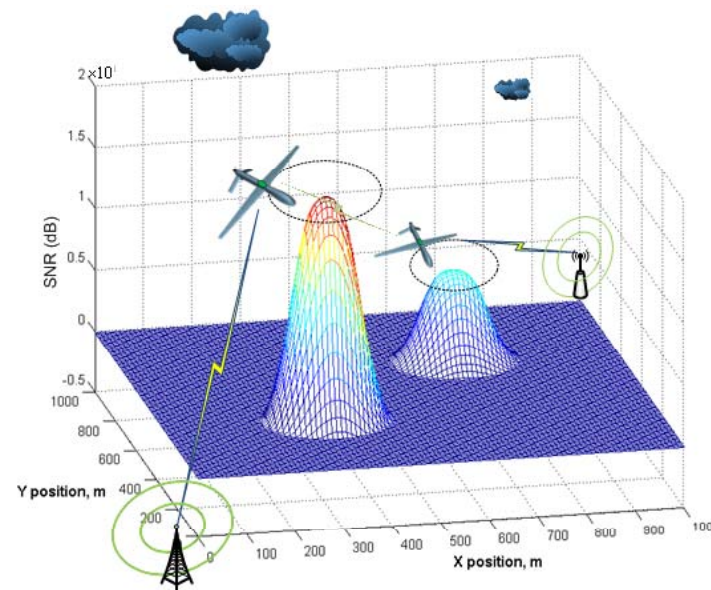
Strategy

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❖ Control Method

- Methods for controlling flying platforms to operate continually at the maximum point of a performance function can be termed real-time optimization or **extremum control**





Approaches I

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❖ Real-Time Optimization

- Cost Function : Communication performance
- Constraint : UAV positioning equation

$$\max_{\mathbf{x}_k \in D} J_k(\mathbf{x}_k) \quad \text{subject to } \mathbf{x}_{k+1} = f(\mathbf{x}_k, u_k)$$

□ Cost Function (J)

$$J(\mathbf{x}_k) = J(x_k, y_k, z_k, \phi_k, \mathbf{x}_{node,i})$$

$\mathbf{x}_{node,i}$ = communications nodes (x_k, y_k, z_k, ϕ_k) = UAV position and attitude (bank)

□ Equations of 3D/2D UAV Motion

$$f(\mathbf{x}_k) : \begin{cases} x_{k+1} = x_k + v \cos(\psi_h) \Delta t \\ y_{k+1} = y_k + v \sin(\psi_h) \Delta t \end{cases}$$

where v is body-axis speed and ψ_h is the yaw angle of the vehicle



Approaches I

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❖ Real-Time Optimization

- If partial derivatives of the cost function are known
- Solution: Extremum Control (Gauss-Newton Optimization)

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{u}_k = \mathbf{x}_k - \alpha_k \mathbf{H}_k^{-1}(\mathbf{x}_k) \nabla J(\mathbf{x}_k)$$

$$\text{where } \mathbf{H}_k = h_{ij}(\mathbf{x}_k) = \frac{\partial^2 J}{\partial x_{i,k} \partial x_{j,k}}(\mathbf{x}_k), \quad \nabla J(\mathbf{x}_k) = \left(\frac{\partial J}{\partial x_{1,k}}(\mathbf{x}_k), \quad \dots, \quad \frac{\partial J}{\partial x_{n,k}}(\mathbf{x}_k) \right)^T$$

- Issue: 3-D Complex Optimization Problem

$$J(x_k, y_k, z_k, \phi_k, \mathbf{x}_{node,i}) = J(\phi_k, \|\mathbf{d}\|)$$

$$\text{where } \|\mathbf{d}\| = \sqrt{(x_{uav} - x_{node})^2 + (y_{uav} - y_{node})^2 + (z_{uav} - z_{node})^2}$$



Methodology

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❖ Gradient-Type Extremum Control

- Measured SNR is discontinuous and slow (1 Hz)
- Subjective to noise and cluttered environment
- Affected by the orientation of a UAV (fast maneuver)

✓ Computation of gradient/hessian values is nontrivial

❖ Approaches and Solutions

➤ Mathematical Communications Modeling

- Provide continuous reference values at fast mode
- Predict a maximum operation point

➤ Model-Free Adaptive Extremum Control

- Gradient is obtained by numerical method without model
- Robust to noise and cluttered environment



Milestones

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❖ Motivations

❖ Communication Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results





SNR Model for Cost Function

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□ Why Signal-to-Noise Ratio Model

$$C = W \log_2(1 + SNR) : \text{Shannon-Hartley Theorem}$$

where C is channel capacity (bits per second)

W - bandwidth (Hz) of the channel

✓ Channel capacity (C) is proportional to the SNR and the bandwidth (W)

□ Signal-to-Noise Ratio (SNR) Model

$$SNR(dBm) = \frac{P_r(dBm)}{P_n(dBm)} = \left(\frac{\lambda}{4\pi \|\mathbf{d}\|} \right)^2 \frac{G_t G_r}{L_{ap}}$$

where $P_r(dBm)$ is the receiver power $P_n(dB)$ is noise power (-95 dBm)

$G_r(dB)$ is receiver antenna gain $G_t(dB)$ is transmitter antenna gain

$\lambda = c / f$ where f is the transmission frequency $c = 3 \times 10^8$ m/s $\|\mathbf{d}\|$ = distance

$$L_p(dB) \equiv (4\pi \|\mathbf{d}\| / \lambda)^2 \text{ is path loss}$$

$$L_{\varphi}(dB) \text{ is antenna pattern loss}$$

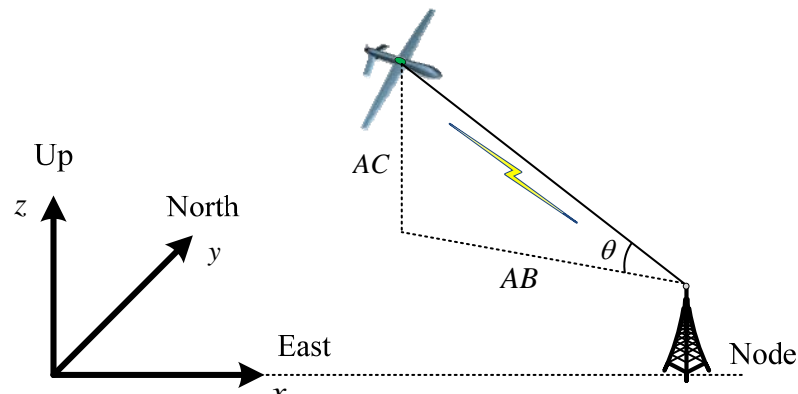


Antenna Pattern Loss on SNR

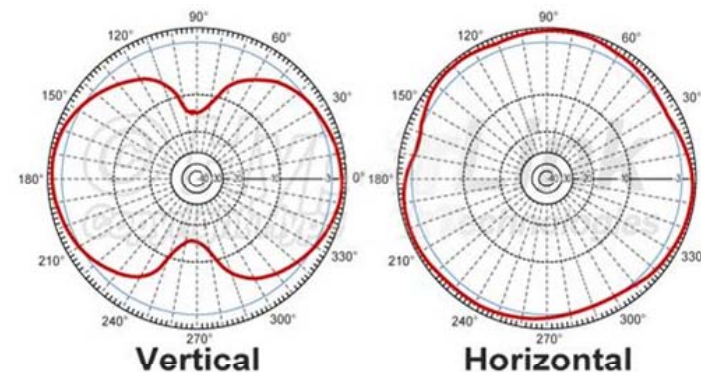
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□ Model for UAV Orientation Effects



Effect of the Arrival Angle
on Antenna Pattern Loss



Antenna Pattern Loss in the Horizontal and Vertical Planes

➤ Antenna Pattern Loss : Function of Arrival Angle $\gamma_i(t)$

$$\gamma_i(t) = -\theta_i(t) - \phi(t) \sin(\varphi_i(t) - \psi(t))$$

which is the angle between the incident ray and horizontal wing of a UAV

$$\theta_i(t) = \tan^{-1} \left(\frac{(z(t) - z_{node,i})}{\sqrt{(x(t) - x_{node,i})^2 + (y(t) - y_{node,i})^2}} \right)$$

$$\varphi_i(t) = \tan^{-1} \left(\frac{y(t) - y_{node,i}}{x(t) - x_{node,i}} \right)$$

$\phi(t)$ is the UAV bank angle

$\psi(t)$ is the heading angle of the UAV

$\varphi_i(t)$ is the bearing angle

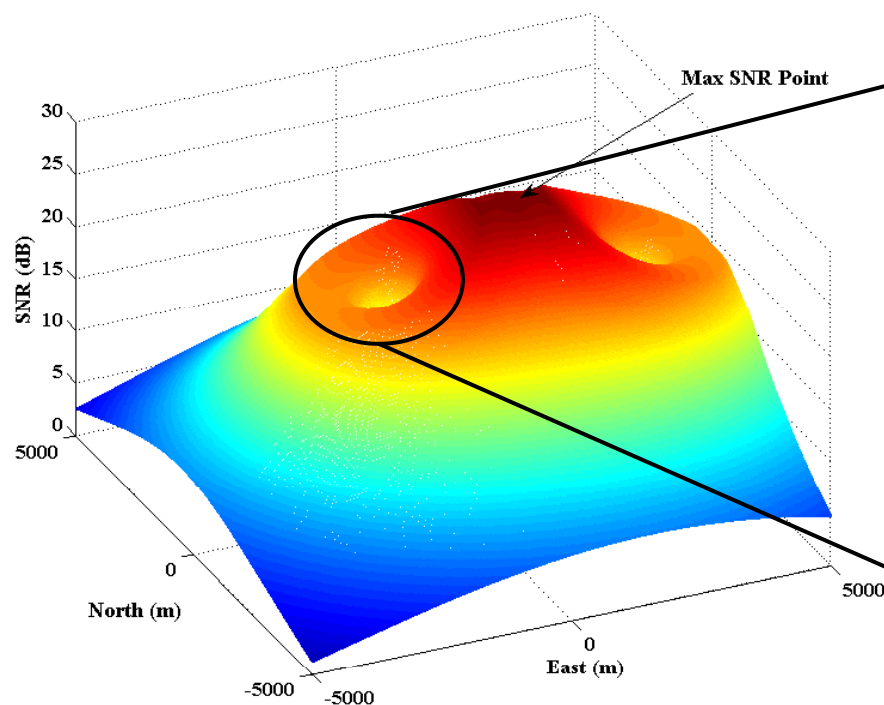


SNR Map Example

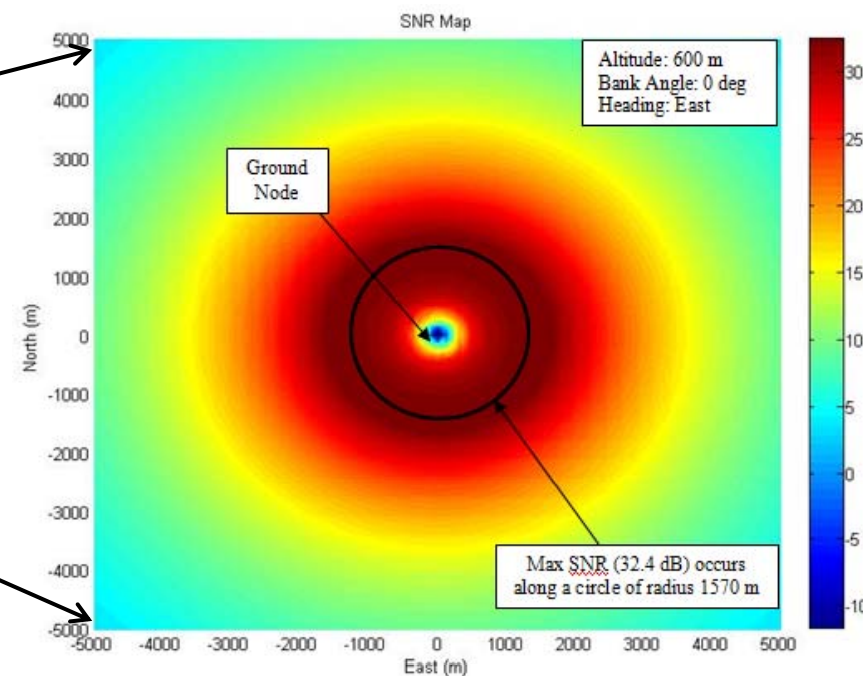
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- ❑ Static SNR Map in East-North-Up coordinates
 - Fixed altitude, heading & bank angle
 - Path loss, Antenna pattern loss



SNR Map (3-D View)



SNR Map (2-D Top View)



Milestones

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❖ Motivations

❖ Communication Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results



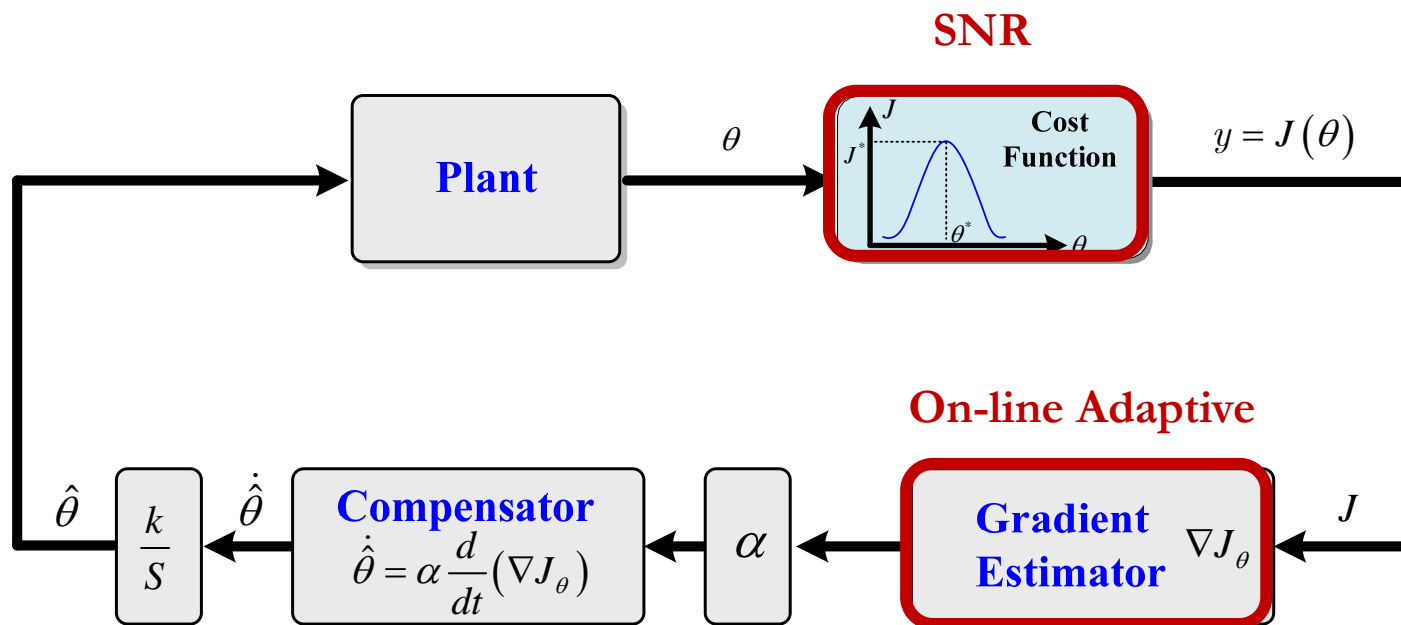


Self-Tuning Extremum Control

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- Use **on-line gradient estimation** of SNR function to drive the set point to its max location
- On-line estimator does not require a precise model





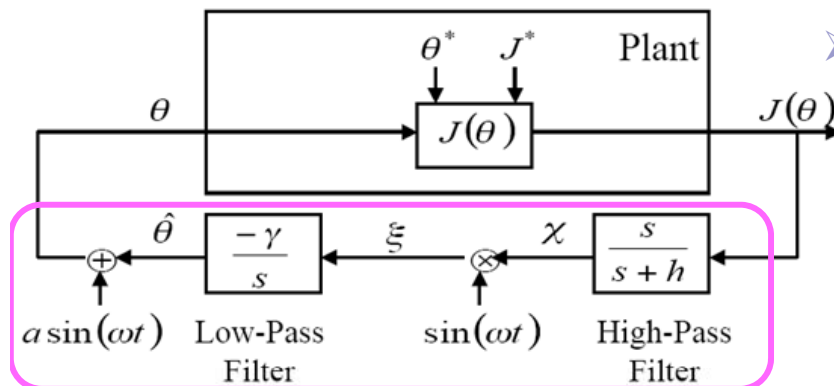
On-Line Gradient Estimator

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□ Perturbation Based Gradient Estimator

- The purpose is to make $\theta - \theta^*$ as small as possible, so that the output is driven to its minimum J^*



$$J(\theta) = J^* + \frac{J''}{2} (\theta - \theta^*)^2, \quad J'' > 0$$

Peak-Seeking Architecture
(Stability Proof by Krstic, 2001)

- Applying **high-pass filter (differentiator)** gets rid of constant term and leads to

$$y_H \approx a \frac{\partial J}{\partial \theta} \bigg|_{\theta=\hat{\theta}} \sin wt$$

➤ How It Works ?

- Let $y = J(\theta)$ be a general mapping function
- Assume $\hat{\theta}$ be a current parameter
- **Perturbation** $a \sin wt$ around $\hat{\theta}$ leads to

$$y = J(\hat{\theta} + a \sin wt) \approx J(\hat{\theta}) + a \frac{\partial J}{\partial \theta} \bigg|_{\theta=\hat{\theta}} \sin wt$$



On-Line Gradient Estimator

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- Demodulating y_H with $\sin wt$ divides the signal into a low-frequency signal and high-frequency signal

$$\varsigma = \frac{1}{2}a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}} - \frac{1}{2}a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}} \cos 2wt$$

- Applying low-pass filter (integrator) gets rid of the sinusoidal term and provides an estimate of the gradient of $J(\theta)$

$$y_L \approx \frac{1}{2}a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}}$$

- The estimated gradient can be expressed by the parameter change

$$\dot{\hat{\theta}} = k \frac{1}{2}a \frac{\partial J}{\partial \theta} \Big|_{\theta=\hat{\theta}}$$

Self-Tuning Estimator

- Denote $\tilde{\theta} = \hat{\theta} - \theta^*$ the convergence error, and taking a derivative of the errors leads to

$$\dot{\tilde{\theta}} = \dot{\hat{\theta}} \approx k \frac{1}{2}a J''(\theta^*) \tilde{\theta}$$

- ❖ which become stable with a proper choice of the parameter, a and k i.e., $kaJ''(\theta^*) < 0$



Autonomous Controller Design

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□ How Self-Tuning Extremum Control Works ?

- Key idea is to integrate **an on-line gradient estimator** into an extremum control to get optimal location for UAVs

□ Consider 2-D Motion in $\{I\}$ Frame

$$f(\mathbf{x}_k) : \begin{cases} \dot{x}(t) = v(t) \cos(\psi_h(t)) \\ \dot{y}(t) = v(t) \sin(\psi_h(t)) \end{cases}$$

where v is body-axis speed and ψ_h is the yaw angle of the vehicle

□ Motion with Constant Speed

$$\begin{aligned} x(t) &= v \cos(\psi_h(t)) = f_1(\psi_h(t), x_0) \\ y(t) &= v \sin(\psi_h(t)) = f_2(\psi_h(t), y_0) \end{aligned}$$

where $v = \text{const}$



Autonomous Controller Design

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- Then SNR function becomes an implicit function of heading angle

$$J = SNR(x(t), y(t)) = SNR(x(\psi_h(t)), y(\psi_h(t))) \\ = J(\psi_h(t))$$

- Gradient Descent Extremum Control is expressed by

$$\psi_{k+1} = \psi_k + \alpha_k \nabla J_{\psi}$$

where $\nabla J_{\psi} = \partial J / \partial \psi \in \mathbb{R}$

- Assume that SNR is a quadratic function

$$J(\hat{\psi}(t)) = J^* + \frac{\mu}{2} (\hat{\psi}(t) - \psi^*)^2 + w(t)$$

$\hat{\psi}(t)$ is the current heading angle estimate

J^* is the maximum attainable value of the cost function, $w(t)$ is a zero-mean white noise

μ is the sensitivity of the quadratic curve **Unknown**

ψ^* is the heading angle maximizing J



Adaptive Convergence Control

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➤ Adaptive Convergence Rate α_k

□ Armijo-Wolfe Conditions

$$J(\mathbf{x}_k + \alpha_k \mathbf{d}_k) \leq J(\mathbf{x}_k) + c_1 \alpha_k \mathbf{d}_k^T \nabla J(\mathbf{x}_k)$$

$$\mathbf{d}_k^T \nabla J(\mathbf{x}_k + \alpha_k \mathbf{d}_k) \geq c_2 \mathbf{d}_k^T \nabla J(\mathbf{x}_k)$$

where $0 < c_1 < c_2 < 1$

the *Armijo* condition that prevents steps that are too long

the *Wolfe* condition which restricts steps that are too short

□ Adaptive Convergence Control Law

$$\alpha_{k+1} = \gamma \alpha_k, \text{ where } \begin{cases} 0 < \gamma < 1, & \text{if } \Delta J_{k+1} > \tau_{tv} \\ \gamma \geq 1, & \text{else } \Delta J_{k+1} < \tau_{tv} \end{cases}$$

where

$$\Delta J_{k+1} = J_{k+1} - J_k \text{ or } d(\nabla J_{\hat{\psi}(t)}) / dt$$

τ_{tv} : a specified threshold value

$$u_{com}(t) = \begin{cases} \dot{\psi}_{com}(t) = \dot{\psi}_{ss} & \text{if } |\dot{\psi}_{com}(t) - \dot{\psi}_{ss}| = v / R_{ss} \leq \varepsilon_{ss} \\ \dot{\psi}_{com}(t) = \dot{\psi}_{ss} + \mu \gamma \alpha(t) \dot{\hat{\psi}}(t) & \text{other} \end{cases}$$



Autonomous Heading Controller Design

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□ Applying On-Line Gradient Estimator

$$\nabla J_{\hat{\psi}(t)} \equiv \frac{\partial J(\hat{\psi}(t))}{\partial \hat{\psi}(t)} = \mu(\hat{\psi}(t) - \psi^*) , \quad \frac{d}{dt}(\nabla J_{\hat{\psi}(t)}) = \mu(\dot{\hat{\psi}}(t))$$

□ Then the extremum controller is expressed by

$$\begin{aligned} \dot{\psi}_{com}(t) &= \frac{d\psi(t)}{dt} = \alpha(t) \frac{d}{dt}(\nabla J_{\psi}) \\ &= \mu \alpha(t) \dot{\hat{\psi}}(t) \end{aligned}$$

On-line Gradient Estimator

$\alpha(t)$: step length along the direction ∇J Optimal value can be obtained by *Armijo-Wolfe* conditions

□ Orbit Circle Guidance at Final Steady-Stage

$$u(t) = \begin{cases} \dot{\psi}_{com}(t) = \dot{\psi}_{ss} & \text{if } |\dot{\psi}_{com}(t) - \dot{\psi}_{ss}| = v / R_{ss} \leq \varepsilon_{ss} \\ \dot{\psi}_{com}(t) = \dot{\psi}_{ss} + \mu \alpha(t) \dot{\hat{\psi}}(t) & \text{other} \end{cases}$$

ψ_{ss} is introduced to guarantee that the UAV will orbit with a constant radius R_{ss} at the final stage.

$R_{ss} = v / \dot{\psi}_{ss}$: a final approach circle radius.



Milestones

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❖ Motivations

❖ Communication Modeling

❖ Self-Tuning Extremum Control

❖ Flight Test Results





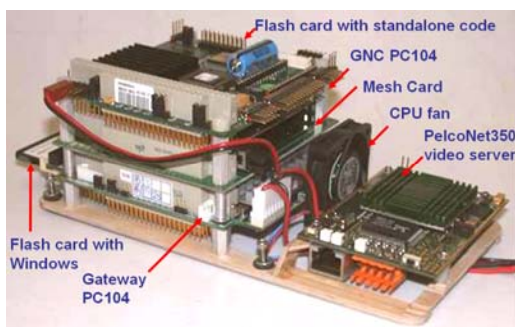
Flight Test Systems

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Rascal 110 UAV (ARF Airframe)



Onboard PC104 & Payload Stack



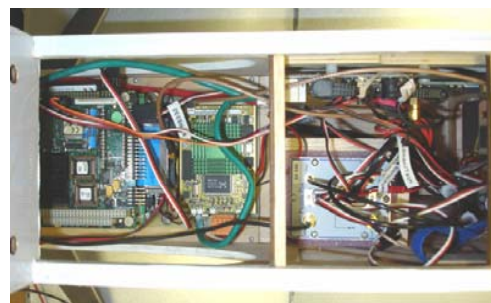
Piccolo Plus Autopilots



2-Stroke Gas Engine



Engine Mount



Avionics bay of Rascal UAV

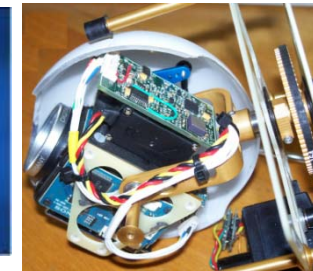


Mobile GCS

- ❖ **Rapid Flight Test Design Keys**
- ❑ Reduce development time
- ❑ Upgrade is flexible
- ❑ Convenience of high level programming



Tracking antenna and Wave Relay mesh link



Gimbal Camera



Model Verification Flight Test

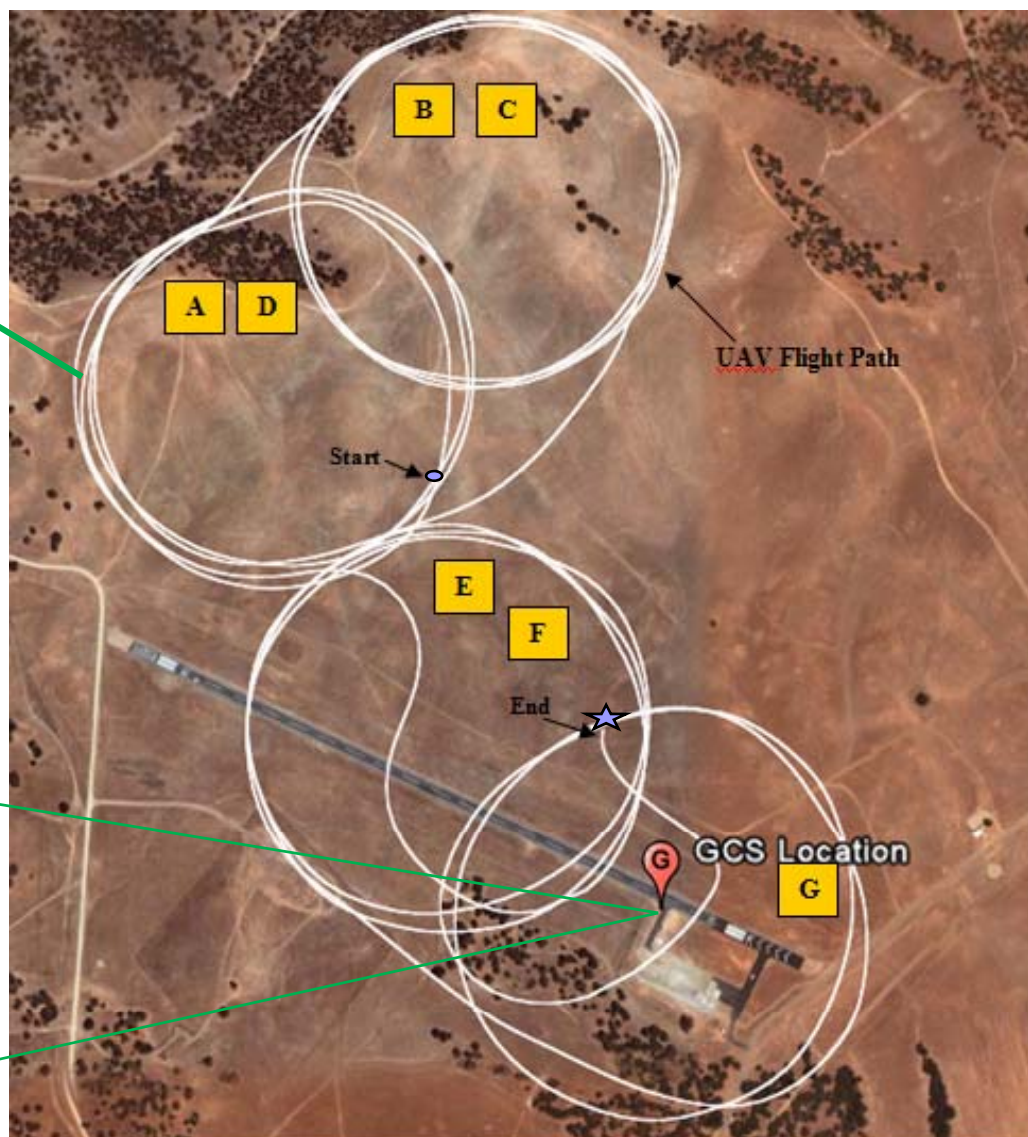
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3 dB Omni-
Directional Antenna

9 dB Sector Antenna

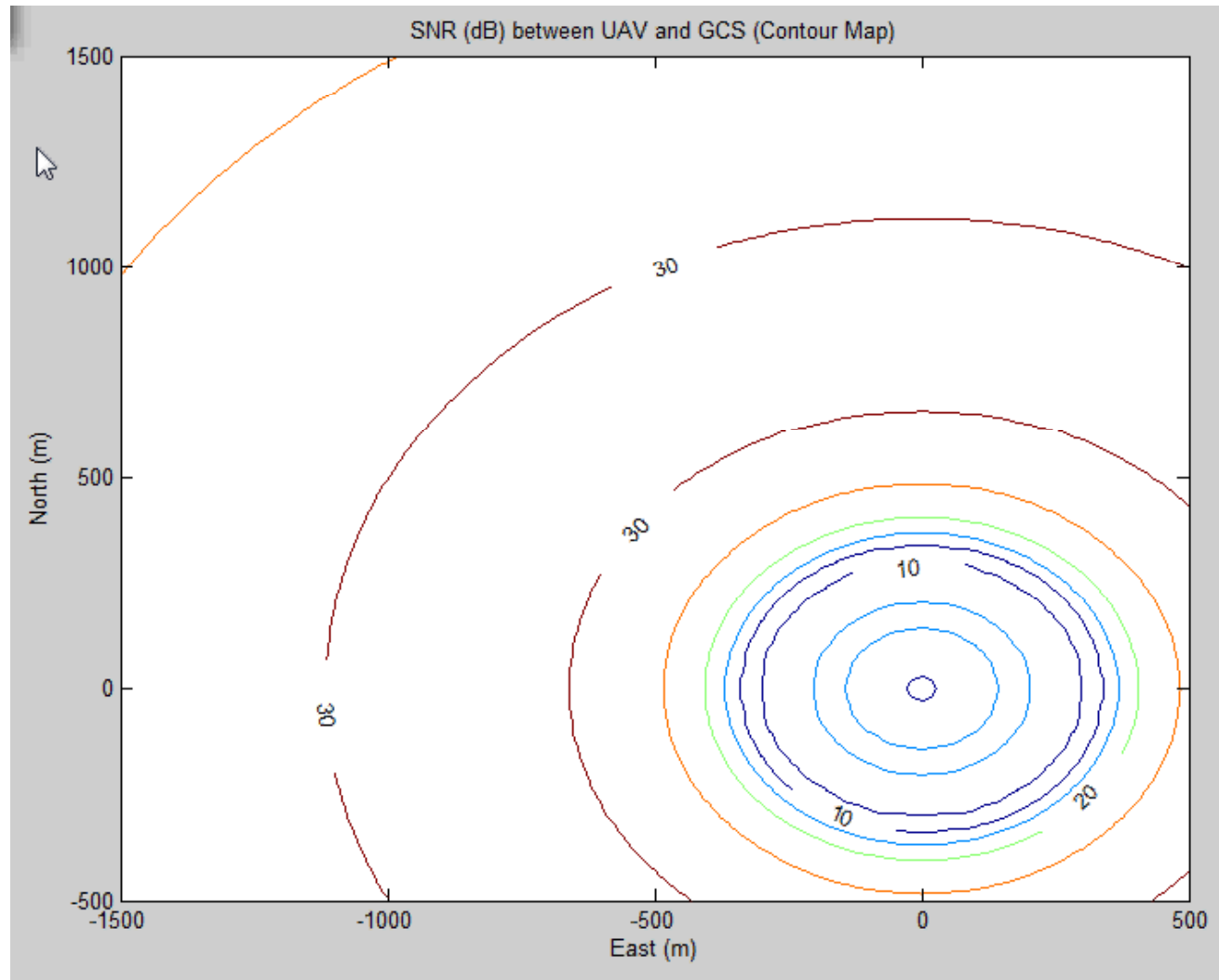




SNR Model Verification

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Movie

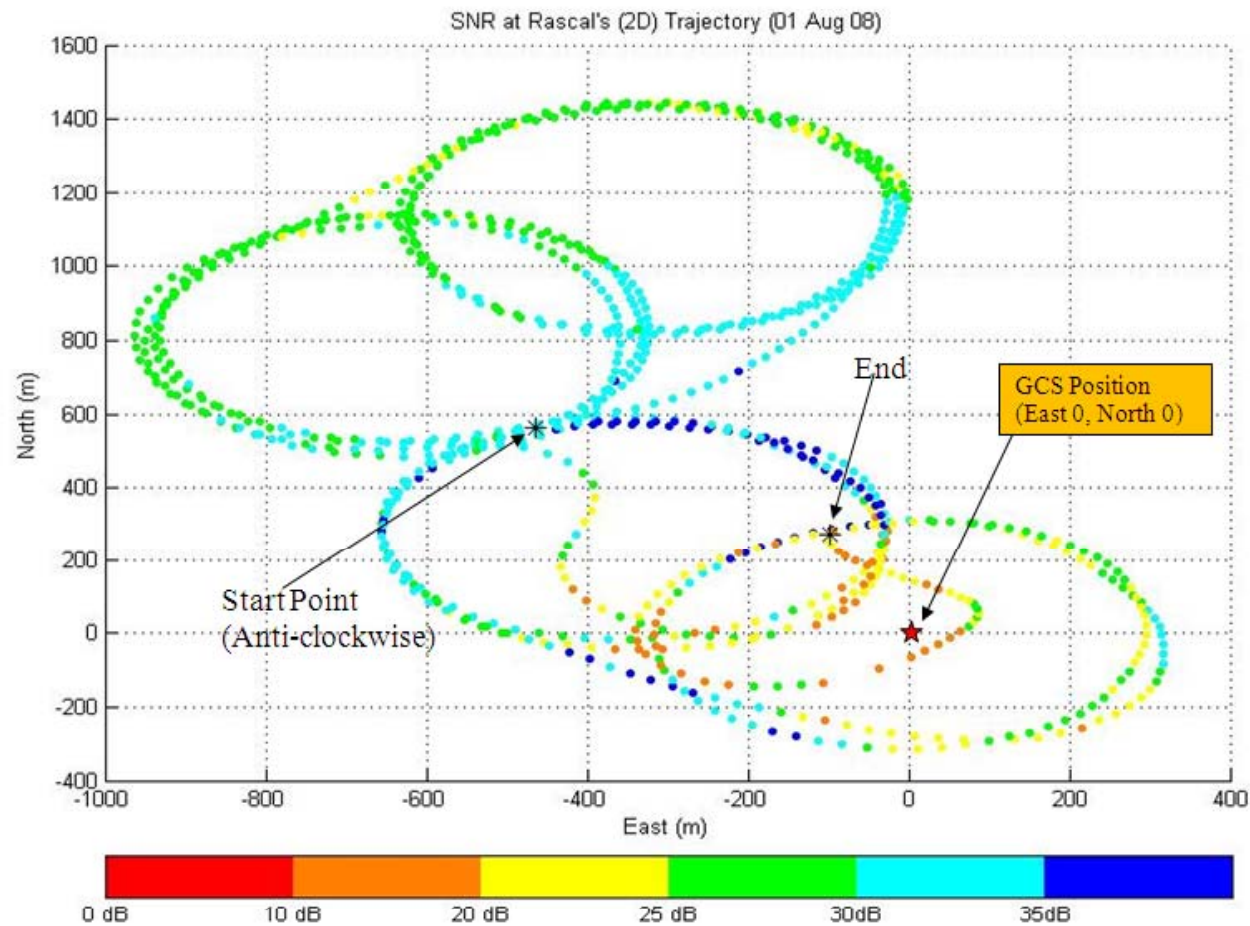
SNR Model Verification with respect to UAV Trajectories



SNR Model Verification

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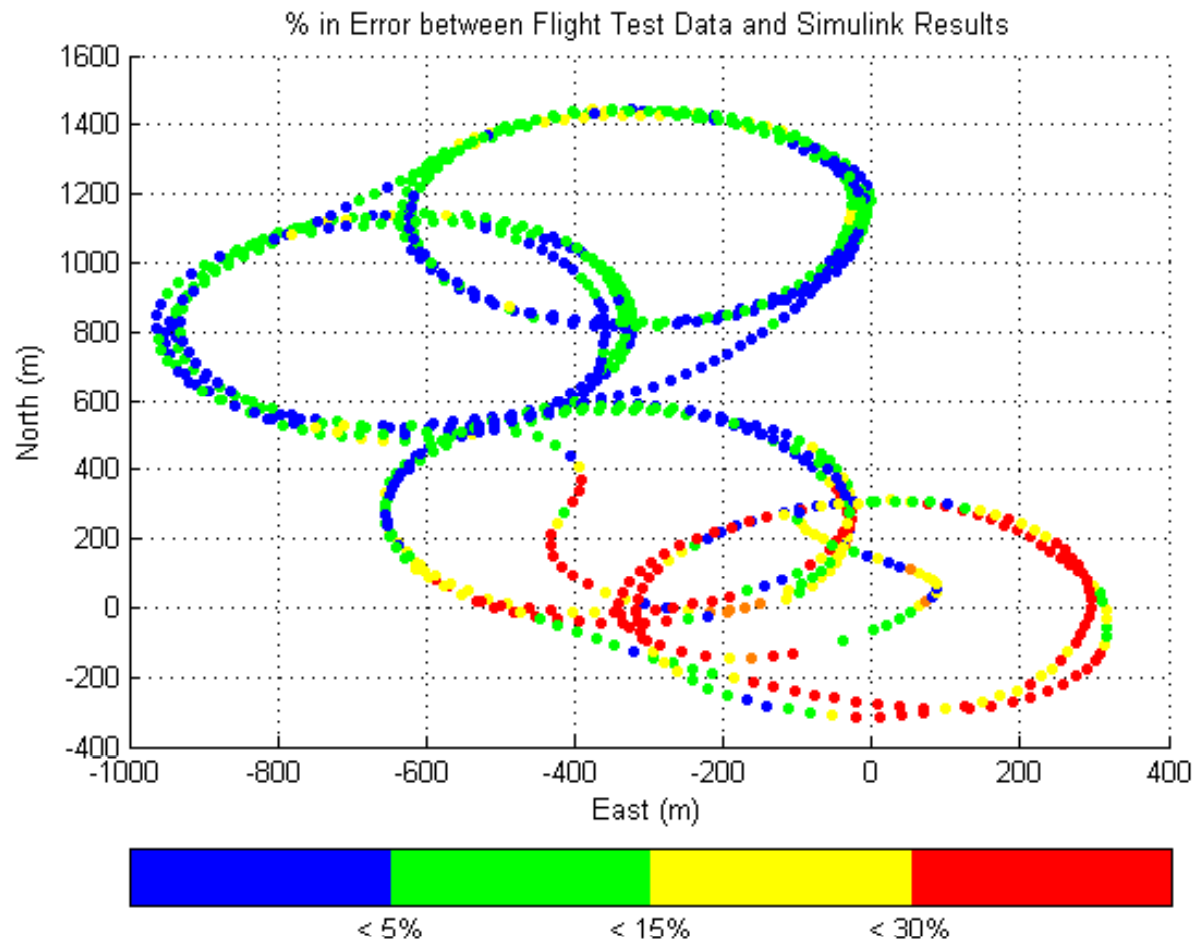
SNR Variation with respect to UAV Trajectories



Comparison with SNR Model

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SNR Error Plots Between Real and Model Values

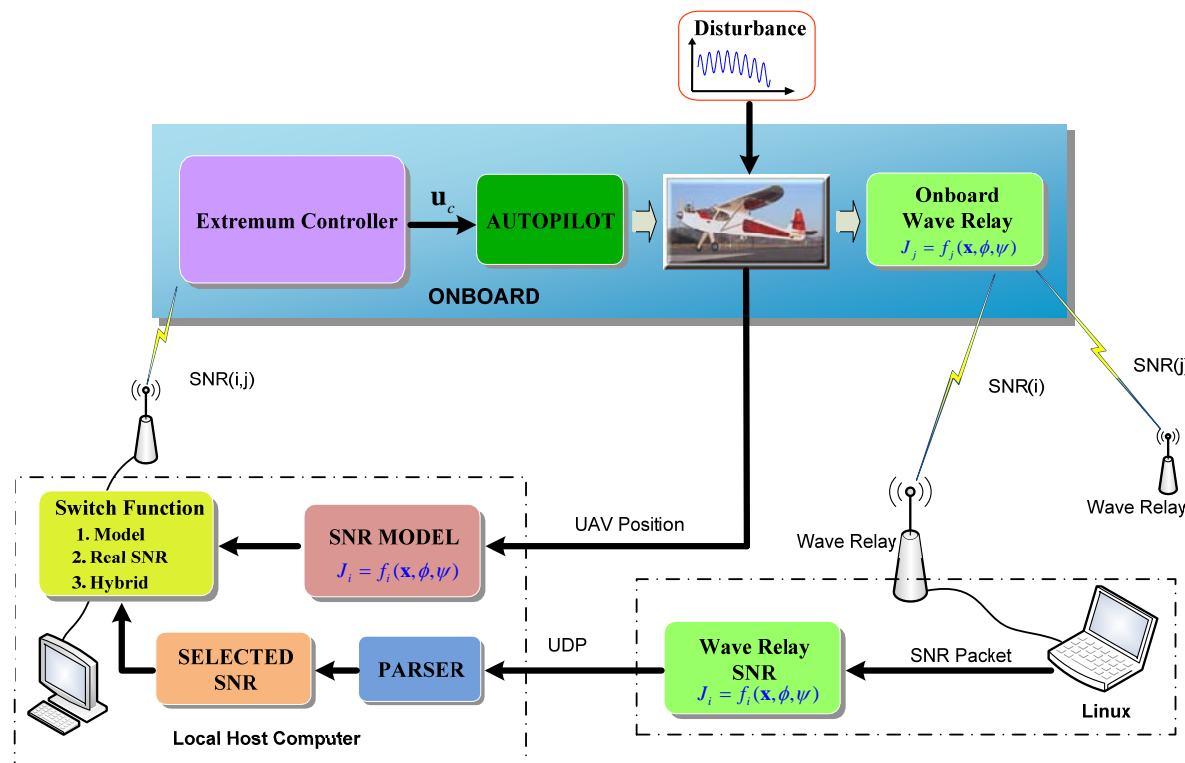


High Band Comms Flight Test

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- ❖ Flight Test (Nov. 20, 2008)
 - Validate the designed onboard adaptive self-tuning controller & the communication models



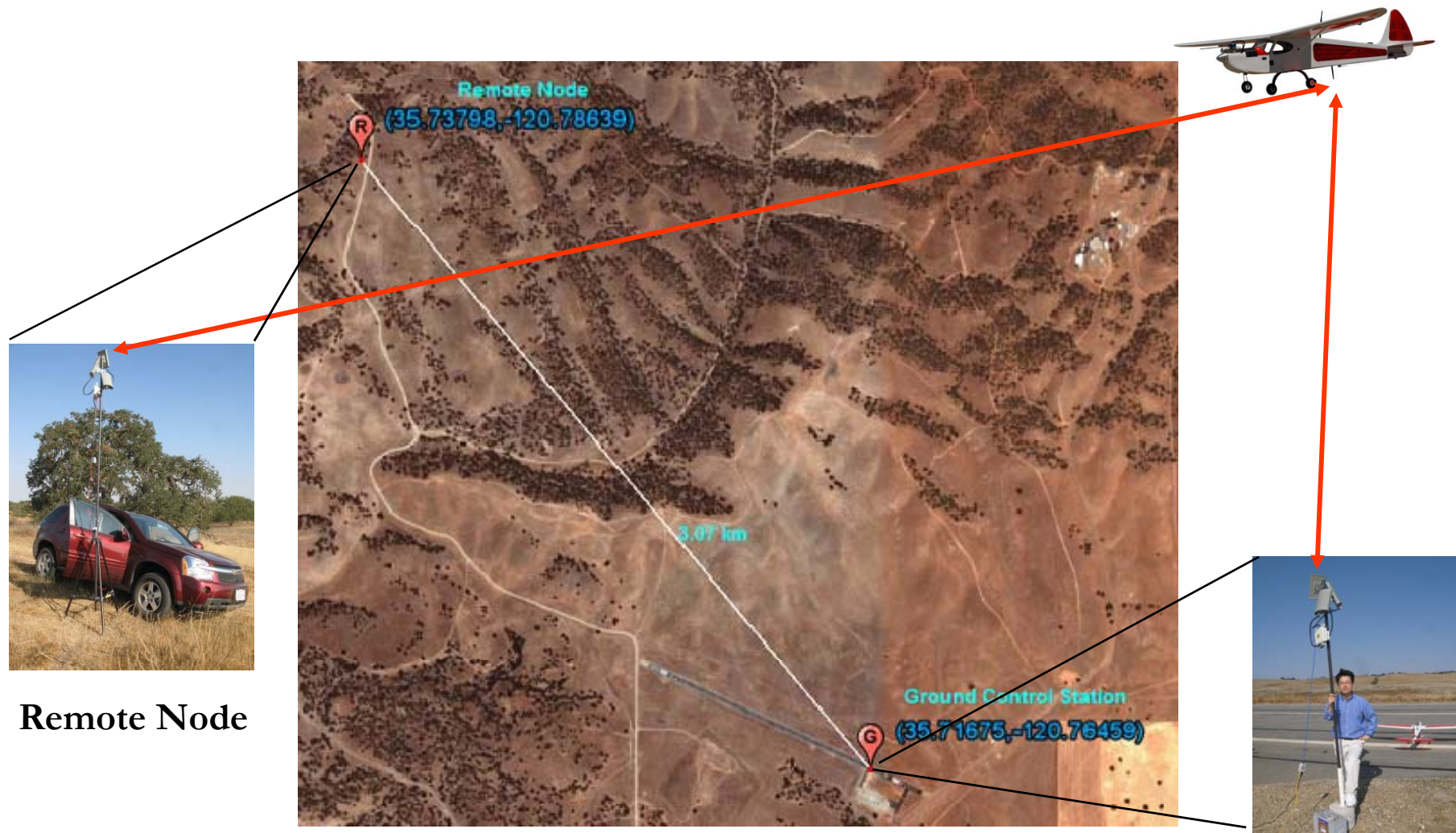
Network Coverage Control using Extremum-Seeking Control



Flight Test Set-Up

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Remote Node

Sensor Node Locations & Flight Setup in Camp Roberts

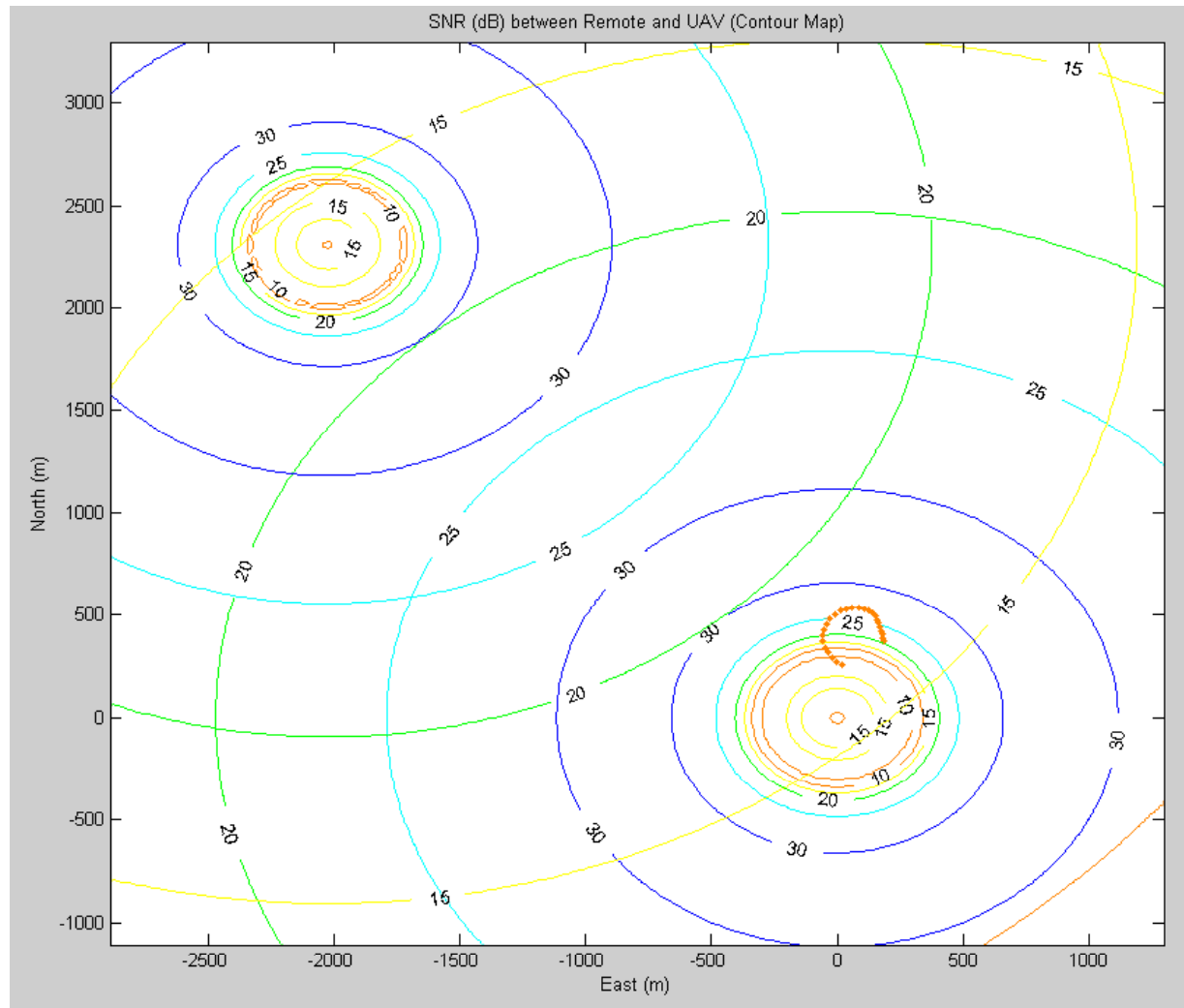
GCS



UAV Trajectory over SNR MAP

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(Movie)

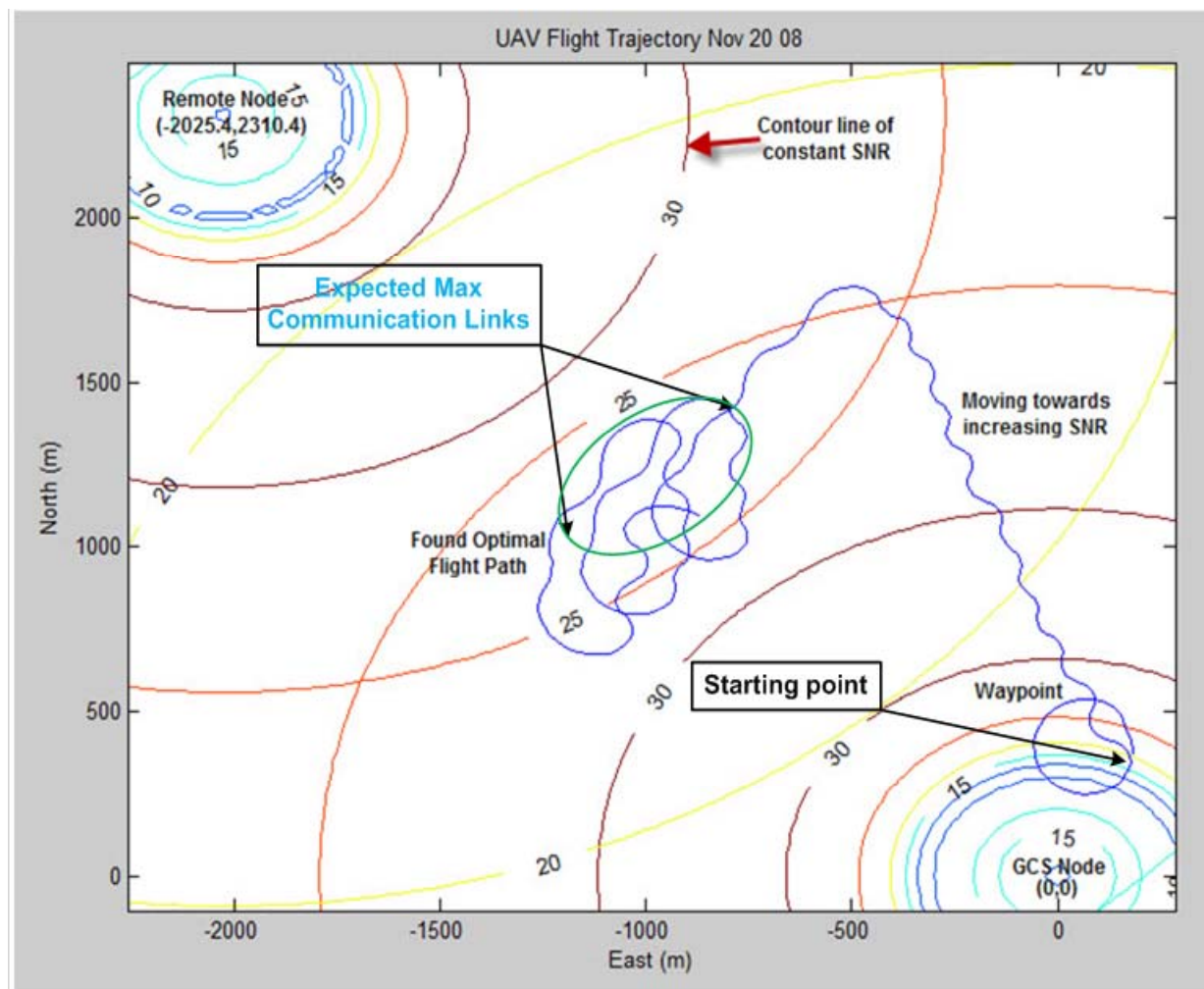
UAV Trajectory Control for Max Communication Links (SNR)



UAV Path over SNR Map

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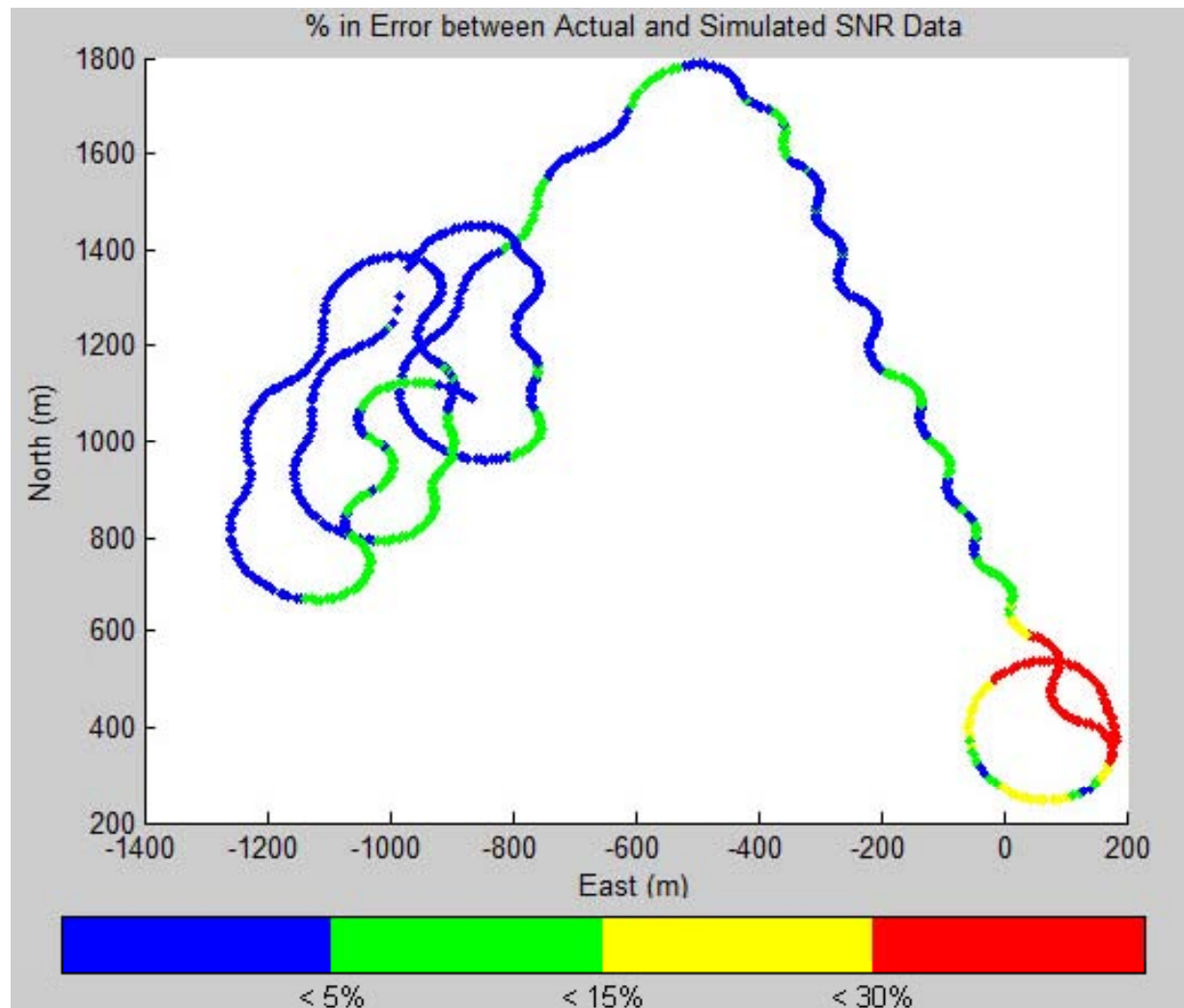
Plot of UAV Trajectory over SNR Maps



SNR Model Errors

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Plot of SNR Errors Between Model and Observation Ones



Conclusions

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□ Communication Propagation Model

- Communication propagation model was developed, which include the effects of the path loss, antenna pattern loss, and the orientation of aerial platforms
- Proposed models were validated through real flight tests

□ Self-Tuning Extremum Control for UAVs Location

- On-line adaptive gradient estimator was integrated into an extremum control architecture
- Proposed self-estimating extremum control is robust to even low signal-to-noise ratio signal
- Effectiveness of the self-tuning optimizer was validated through real time flight tests

□ Applicable for Decentralized Network Coverage Control